Frequency comb and microwave generation with a full phononic bandgap 1D optomechanical crystal cavity

(Student Paper)

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ABSTRACT

In this work we show that a silicon optomechanical crystal cavity can be used as an optoelectronic oscillator when driven to the phonon lasing condition with a blue-detuned laser. The optomechanical cavity is designed to have a breathing like mode vibrating at $\Omega_m/2\pi$ =3.897 GHz in a full phononic bandgap. Our measurements show that the first harmonic displays a phase noise of -100 dBc/Hz at 100 kHz. Stronger blue-detuned driving leads eventually to the formation of an optomechanical frequency comb, with lines spaced by the mechanical frequency. The measured phase noise grows up with the harmonic number, as in classical harmonic mixing. We present real-time measurements of the comb waveform and show that it can be adjusted to a theoretical model recently presented. Our results suggest that silicon optomechanical cavities can play a role in integrated microwave photonics.

Keywords: optomechanical crystal cavity, phononic bandgap , optoelectronic oscillator, frequency comb.

1 INTRODUCTION

Cavity optomechanics studies the interaction between light and sound waves simultaneously confined in a cavity [1], [2]. In an optomechanical cavity (OMC), confined mechanical waves can coherently modulate an optical signal at MHz and even GHz frequencies via optomechanical interaction. Thus, OMCs could become relevant in microwave photonics, a discipline addressing the manipulation of microwave signals in the optical domain [3]. Furthermore, since OMCs are nonlinear elements, multiple harmonics of the fundamental mechanical vibrations can be overimposed on the optical signal [4], a phenomenon that has been interpreted theoretically as an optomechanical frequency comb (OFC) [5].

Here, we first demonstrate an OMC on a silicon nanobeam having a breathing-like mechanical mode vibrating close to 4 GHz with a high g_0 and placed in a full phononic bandgap [6]. Then, via blue-detuned laser pumping we demonstrate phonon lasing of this fundamental mechanical mode. Stronger pumping of the cavity leads to the observation of a series of harmonics forming an OFC in both the optical and RF spectrum. We measure the phase noise of the generated microwave tone and show that the OMC can be used as an optoelectronic oscillator. In addition, the phase noise of the harmonics degrades with the harmonic number as in standard harmonic mixing. We also perform real-time measurements of the temporal traces using a GHz-bandwidth oscilloscope and show that they are in good agreement with a theoretical model of an OFC. Our work paves the way for the use of silicon OMCs as ultracompact and ultraweight elements for microwave photonics.

2 OPTOMECHANICAL FREQUENCY COMB

The optomechanical cavity that we exploit here consist in a suspended silicon nanobeam with one-dimensional (1D) periodicity. The key idea is to have OM mirrors (that prevent leakage of both photons and phonons) on each nanobeam side whilst optical and mechanical resonant modes are confined in the central region, also having a good overlap between them. Our structure results of an optical mode at λ_r =(1522.3±0.3) nm with an optical quality factor of $Q_o = 5 \times 10^3$, presented in Fig. 1(a), and a mechanical mode at $\Omega_m/2\pi$ =3.897 GHz with an optomechanical coupling rate of $g_0/2\pi = (660 \pm 70)$ kHz, depicted in Fig. 1(b). In addition, we have design our structure in order to have a full phononic bandgap in order to reduce the phonon leakage. Because of fabrication imperfections, the fabricated structures tend to be a bit different from the nominal ones. Thus, in order to ensure that our mechanical mode is confined in this full phononic bandgap, we simulated, in Fig. 1(c), the phononic band diagram from the profile extracted from a Scanning Electron Microscopy (SEM) image, which is shown (see Fig. 1(d)). Here, we can see that we have this phononic bandgap were our experimental mechanical mode lies.

The mechanical mode can be driven to the phonon lasing regime under proper conditions (see Section 3). When driving the OMC with a blue-detuned laser with respect to the optical resonance at even higher power,

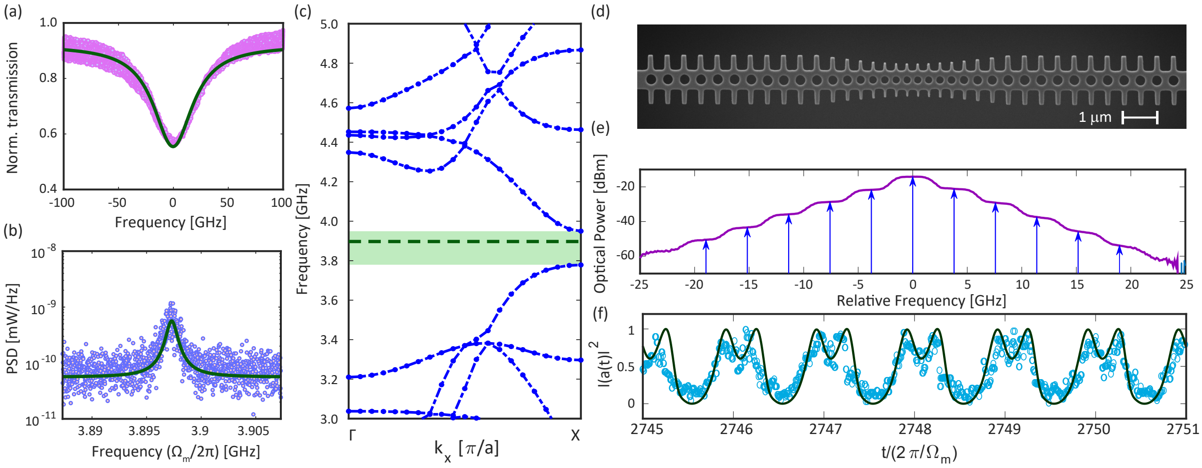

Figure 1. (a) Optical experimental resonance trace (purple) and Lorenztian fit (dark line). (b) Power spectral density of the mechanical resonance confined in the total bandgap. (c) Phononic band diagram for the real profile mirror unit cell extracted from the SEM image, including the experimental measured frequency of the mechanical mode (dashed line). (d) SEM image of the fabricated OM cavity. (e) Recorded optical spectrum in purple showing a set of peaks corresponding to different harmonics represented in blue at the expected position. (f) Comparison of the experimental (dots) and the theoretical (solid line) temporal OM-generated OFC traces.

higher-order harmonics can be observed in the detected signal. This closely resembles an optical frequency comb (OFC) of OM nature, which has been recently analyzed theoretically in [5]. We measured up to the fifth harmonic, which can be seen in the optical spectrum of the generated OFC in Fig. 1(e). In addition, we can also study the optical traces of the generated OM comb in the time domain where the dynamics generation can be described by a set of coupled equations describing the time evolution of the optical and mechanical mode amplitude [5]. The comparison between the acquired experimental traces and the theoretical model are presented in Fig. 1(f), showing a good agreement.

3 OPTOELECTRONIC OSCILLATOR

High-quality microwave sources, which are required for a number of applications, are typically made by applying frequency multiplication to an electronic source. This requires a cascade of frequency-doubling stages, which means that the power of the final signal is greatly reduced. Recently, different techniques to produce microwave tones via optical means have been proposed resulting in optoelectronic oscillators (OEO). Amongst the different techniques to build an OEO, we propose an OEO obtained from an OM cavity when pumped with a blue-detuned laser source. We made this experiment with the cavity proposed in the last section and we measured the resulting noise figure, as in Fig. 2(a), where we reach the comb regime. For the first harmonic shown in Fig. 2(b), the noise figure becomes as low as (-100$\pm$1) dBc/Hz at 100 kHz, which is a remarkable good value for an OEO oscillating at GHz frequencies. This performance is on par with some commercial mid-range devices, such as the Agilent N5183AMXG that displays a phase noise of -102 dBc/Hz at 100 kHz offset for a 10 GHz frequency [7]. We have also measured the phase noise of the different harmonics, as shown in Fig. 2(c). An RF spectra showing the first five harmonics is also depicted in Fig. 2(d). In principle, the harmonic mixing process will result in an added phase noise of $20 \times log(m)$ with respect to that of the first harmonic. It can be seen that the previous rule is well satisfied in our device.

4 CONCLUSIONS

In summary, we have demonstrated a new silicon-chip OMC implemented with a large OM coupling rate for a GHz mode within a full phononic bandgap. This OM cavity can perform as an ultracompact OEO at a microwave frequency around 4 GHz. Notice that our device is a free-running or open-loop OEO: the device generates an RF tone and there is no any feedback loop to improve the frequency stabilization. Operation at cryogenic temperatures would improve the phase noise [8] as a result of the enhancement of the mechanical Q factor because of the full phononic bandgap. In addition, the preliminary demonstration of the OFC paves the way towards synthesis of microwave signals beyond the generation of pure cw tones. The main advantages of the OMC approach for microwave signal processing are its extreme compactness and low weight, highly desirable in space and satellite applications, and its compatibility with silicon electronics and photonics technology.

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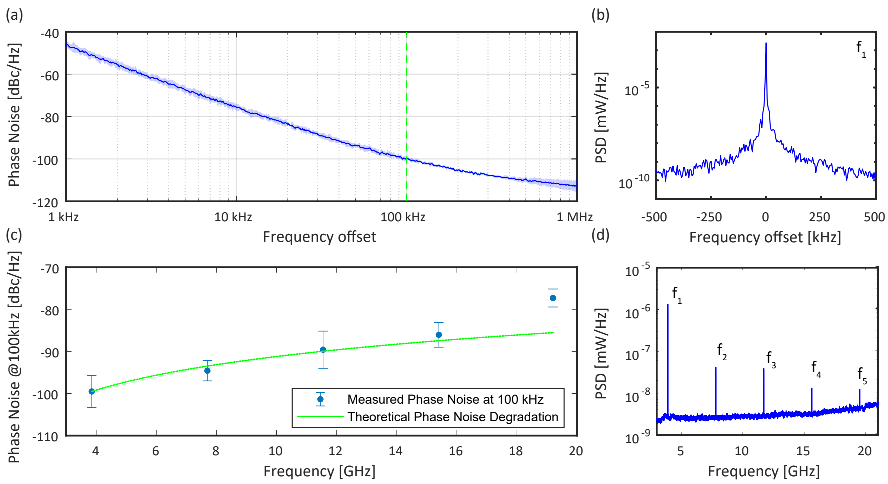

Figure 2. (a) Mean phase noise of the generated microwave tones in blue and its standard deviation represented by the shadowed area. The noise figure at 100 kHz is (-100$\pm$1) dBc/Hz for the first harmonic. (b) Linear scale of the first harmonic centered at 3.87 GHz. (c) Phase noise of the different harmonics of the OFC with the theoretical phase noise degradation of $20 \times log(m)$ with respect to that of the 1st harmonic. (d) RF spectra of the generated OFC showing the different obtained harmonics.

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